



Interfaces with Other Disciplines

On the effectiveness of emission penalties in decentralized supply chains

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ABSTRACT

In recent years, the emission of harmful pollutants, such as greenhouse gases, due to industrial activities have received considerable interest from both business and scientific communities. As a result, an increasing number of voluntary and governmental initiatives that penalize emission generated by businesses have been witnessed. In this research, we examine the extent to which imposing penalties on the emission of harmful pollutants can successfully reduce overall emissions in decentralized supply chains. Using a buyer–vendor supply chain framework, we show that penalizing each firm for the emissions for which it is directly responsible can sometimes lead to higher overall supply chain emissions. We show that this phenomenon occurs because firms, in their efforts to reduce their own emissions, can make decisions that adversely impact the emissions of other firms in its supply chain. Moreover, we show that centralizing the supply chain—contrary to what one may think at first glance—is not always the appropriate solution to mitigate this effect. We provide some potential remedies and evaluate their relative effectiveness. We also present a detailed numerical example using realistic problem parameter values to examine the extent to which emission reduction efforts by individual firms are successful in reducing overall emissions.

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1. Introduction

There is growing pressure on governments and firms worldwide to reduce the emission of harmful pollutants, such as carbon dioxide, or the consumption of scarce natural resources, such as water, to levels that are deemed environmentally sustainable. Imposing penalties on emissions (For the remainder of the paper, we will use the term “emissions” exclusively. However, our analysis extends to the production of negative externalities, broadly defined, including the consumption of scarce resources.) is one of the mechanisms adopted by a number of countries and regions to achieve these goals. According to a recent report by the [World Bank \(2016\)](#), about 40 national and over 20 sub-national jurisdictions, responsible for almost a quarter of global carbon emissions, have implemented or are scheduled to implement carbon pricing with prices ranging from less than \$1 to \$137 per metric ton. Carbon pricing can be direct in the form of taxes imposed on the emissions of

individual firms or facilities¹, or indirect because of limits (allowances) imposed on the amount a firm or a facility can emit. In the case of the latter, the penalties correspond to the marginal cost of meeting emission caps, the price of purchasing emission *offsets*, i.e., reductions in emissions in one place that can be used to compensate for emissions elsewhere, or the prevailing market price of tradable emission permits in cap and trade-like systems.

Imposing penalties on emissions is also a mechanism that an increasing number of firms have adopted voluntarily in their efforts to mitigate their emissions. For example, several firms have committed to becoming *carbon-neutral* through the purchase of carbon offsets, where a carbon-neutral firm is one that is credited with reducing global emissions by an amount equal to the one it produces. In order to pay for these offsets, some firms, such as Microsoft and Disney, are imposing internal taxes on their business units for the carbon emissions for which these business units are directly responsible; see [DiCaprio \(2013\)](#) and [Davenport \(2013\)](#). Other firms are putting a price on emissions in evaluating the attractiveness of new investments or to justify investments in

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E-mail addresses: xichenxi@umich.edu (X. Chen), saif@umn.edu (S. Benjaafar), adel.elomri@qu.edu.qa (A. Elomri).¹ According to the World Bank report, 14 countries have implemented carbon taxes.

conservation projects or renewable energy. CDP—a not-for-profit organization running a global disclosure system for environmental impacts of investors, companies, cities, states and regions—reports that over 400 companies used internal carbon prices in year 2014 with prices up to \$357 per metric ton (CDP, 2013; 2015). Firms that are water-intensive, such as Coca Cola, are also putting a price on water that is substantially higher than the prevailing price (Fellow, 2013).

Clearly, everything else remaining the same, imposing a penalty on emissions makes *business-as-usual* more expensive and provides an incentive for firms and business units to reduce their emissions. Thus, it is often argued that such penalties should lead to an economy-wide, or firm-wide, reduction in total emissions through the emission reduction efforts of firms or business units. In this paper, we examine the extent of the validity of this premise in the context of a decentralized supply chain, i.e., a supply chain consisting of independent firms or of independent business units within a single firm. Perhaps surprisingly, we find that penalizing each firm for the emissions for which it is directly responsible can under some conditions lead to higher total supply chain emission and for these emissions to increase in the emission penalty. We show that this “paradox” arises because firms, in their efforts to reduce their own emissions, can make decisions that adversely impact the costs and emissions of other firms in the supply chain.

We base our analysis on a buyer-supplier model that has been extensively studied in the supply chain coordination literature, where the buyer and the supplier make decisions regarding the size of order replenishments. We show how the buyer can choose order sizes that reduce its own emissions but increase the emissions of the supplier, with the net effect being an increase in *total supply chain emission* and we provide necessary and sufficient conditions under which this occurs. In Appendix G, we discuss a general model formulation of which the buyer-supplier model we consider can be viewed as a special case. We then present a detailed case study using realistic problem parameter values in which we examine the extent to which this effect could arise in practice. Results show that, for the scenarios considered, emission reduction efforts by the buyer do not always lead to overall emission reduction and, in some cases, do indeed lead to a net increase.

We examine potential remedies that would guarantee that higher penalties would lead to lower overall emissions. Such remedies naturally require that each firm internalizes either partially or fully the cost of the externality it imposes on the other firms. However, we find that while these remedies ensure that higher penalties lead to lower total supply chain emission, they do not guarantee that emissions would be lower than those obtained when firms are penalized only for their own emissions.

A contribution of this paper is in highlighting the possibility for emission penalties (and, more generally, emission reduction efforts) to *backfire* because of supply chain interactions. Existing literature in both operations management and environmental economics treats for the most part cases where the costs and emissions of one firm are unaffected by the emission mitigation efforts of another firm. The recognition that this may not be the case could have implications in how either policy makers or firms go about designing schemes to reduce total supply chain emission and in how emission responsibility should be allocated across the supply chain. Our results also highlight the importance of understanding supply chain interactions in assessing the effectiveness of different approaches to emission mitigation.

Our work is of course not the first to point out that well-intentioned actions can lead to undesirable consequences. In the area of energy conservation, there are several well-known related phenomena. *Jevons' paradox* (or the *rebound effect*) refers to improvements in energy efficiency leading to more energy consumption (see for example Alcott, 2005 and Jevons, 1865).

For example, as air conditioning became more energy-efficient, more residential and office buildings installed air conditioning units, leading to an increase in air conditioning-related energy consumption and not less. The *indirect rebound effect* refers to savings from greater efficiency in one area leading to increased consumption in other more emission-intensive areas (see for example Greening, Greene, & Difiglio, 2000 and Sorrell, 2009). For instance, improved home insulation leads to less household spending on heating, which in turn leads to more spending on other goods and services that may be more energy-intensive, e.g., air travel. The *global rebound effect* refers to reduction in energy consumption in one country leading to lower global prices triggering more consumption in other countries; see for example Sorrell and Dimitropoulos (2008). The *leakage effect* refers to pollution regulation in one country leading to production moving to another country where production is more emission-intensive and regulation is more lax; see for example Babiker (2005). This paper contributes to this discussion by uncovering an effect that appears to be distinct from those described above.

The rest of the paper is organized as follows. In Section 2, we provide a brief review of related literature. In Section 3, we describe the buyer-supplier model and specify conditions under which higher emission penalties lead to higher total supply chain emission. In Section 4, we discuss potential remedies. In Section 5, we present detailed analysis of a case study. In Section 6, we offer concluding comments.

2. Related literature

There is growing literature concerned with issues of sustainability in supply chains; see for example Dekker, Bloemhof, and Mallidis (2012), Tang and Zhou (2012), Drake and Spinler (2013), and Gonzalez, Zhu, Zanoni, and Maculan (2018) for recent reviews. Thies, Kieckhäfer, Spengler, and Sodhi (2018) and Barbosa-Póvoa, Silva, and Carvalho (2018) provide recent reviews for operations research methods in promoting sustainability in supply chains. For example, Barbosa-Póvoa et al. (2018) review the trends and directions of operations research methods applications towards the achievement of sustainable supply chain, and show how these methods are playing a key role in supporting sustainable activities in supply chains. A stream within this literature focuses on emissions. We review some of the most relevant papers below.

This work contributes to the effort within the sustainable supply chain management literature to identify circumstances where emission regulations either are ineffective or have possible unintended consequences. Bouchery, Ghaffari, Jemai, and Dallery (2012) observe numerically that it is possible for total emissions to increase with emission penalty in a decentralized supply chain. In this paper, we provide analytical support to the results of their numerical examples, and insights on when and why this phenomenon occurs. Sunar and Plambeck (2015) consider the impact of a cross border adjustment tax (a tax on the emissions caused by a product's creation and transportation to the border) incurred by an importer. They show that, in the presence of co-products and for a specific type of allocation of emissions among the products, it is possible for a higher tax to lead to higher emissions. This is due to the fact that higher taxes can lead the supplier of the imported good to lower its selling price resulting in more demand and therefore more emissions. Jacobs and Subramanian (2012) study the issue of product recovery across the supply chain. They show that extended producer responsibility regulation may increase the total production quantity and the quantity of virgin material used in a decentralized supply chain due to the difference in collection efficiencies of the manufacturer and the supplier. Krass, Nedorezov, and Ovchinnikov (2013) examine the choice of green technology of a monopolist and find that the effect of emission taxes on green

technology choice may be non-monotone. Cachon (2014) considers the centralized supply chain of a retailer who decides on the number and size of stores, taking into account the costs and emissions incurred by both the retailer and the consumers. He shows that an emission tax would have to be relatively high to affect the design of the retail network. Chen (2018) studies a variation of this problem where consumers are sensitive to traveling time and cost. They show that in an effort to reduce its direct emissions, the retailer may reduce the number of stores, which increases the consumer's traveling emissions and sometimes result in a total emission increase. However, in their paper, the retailer is the only party motivated to reduce emissions. In contrast, we explore a different setting where a buyer and a supplier choose their inventory decisions. We show that emissions may increase even if all parties in the supply chain are subject to an emission penalty, and this increase may be driven by the buyer's decision or the supplier's decision.

Several papers have studied the effective design of emission policies. Caro, Corbett, Tan, and Zuidwijk (2013) consider a setting where multiple firms contribute to total supply chain emission. They address the question of how to allocate emission responsibility among the firms and show that over-allocating emissions, or *double-counting*, is necessary for firms to exert their first-best emission reduction efforts. An important difference between our work and that of Caro et al. is that in their case the emission reduction, or *abatement*, costs of one firm are not affected by the emission reduction effort of another. In our case, this interaction is central to the results we describe. Gopalakrishnan, Granot, Granot, Šosić, and Cui (2016) study emission allocation in a setting where firms are accountable for their own emissions as well as the emissions from all upstream suppliers. Using a cooperative game theory approach, they show that an emission responsibility sharing scheme where the direct emissions of one firm is allocated equally among all its downstream firms is in the core and corresponds to the Shapley value. Their analysis relies on the assumption that, absent emission sharing, firms are held accountable for the emissions of all their upstream suppliers. They also assume that emissions are exogenously specified and not affected by how emission responsibility is allocated and by the corresponding actions of individual firms. In this paper, we consider settings where firms modify their actions in response to allocations and these actions can affect the costs and emissions of all the firms in the supply chain.

This work also contributes to the study of the impact of supply chain coordination on the supply chain emission. This stream often considers a two-echelon supply chain consisting of one supplier and one vendor under varying emission considerations and operational scenarios. With the decentralized supply chain as a reference, coordination mechanisms are then applied to investigate how coordinating the decisions of the supply chain firms can affect (improve or degrade) the environmental impacts of the supply chain. For example, Raj, Biswas, and Srivastava (2018) compare the effectiveness of five types of contacts in a two-echelon supply chain. They show that channel coordinating mechanisms between supplier and buyer is conducive to improve greening and corporate social responsibility level. Peng, Pang, and Cong (2018) study the coordination of a supplier and a manufacturer under cap-and-trade, where the manufacturer faces yield uncertainty. They show that the quantity discount contract can efficiently coordinate the low-carbon supply chain, but the revenue-sharing contract cannot. Ding, Wang, and Zheng (2018) explore possible collaborative mechanism for enhancing sustainability in a two-echelon supply chain under governmental interventions (e.g., emission penalties and/or subsidies). Chan, Lee, and Campbell (2013) use a real case study to show that it is possible for supply chain coordination to simultaneously reduce supply chain cost and improve environmental performance. Similar insights are suggested by Zissis,

Saharidis, Aktas, and Ioannou (2018) in a different buyer-supplier setting. The authors consider a decentralized two-node supply chain, in which one buyer is ordering from a supplier operating under the lot-for-lot policy. They demonstrate that environmentally friendly policies could be also cost saving in the presence of quantity discount incentives. Building on the results suggested by this literature stream, Ghadimi, Toosi, and Heavey (2018) propose a Multi-Agent Systems approach as a mean of automating and facilitating the process of sustainable supplier selection and order allocation resulting in a more co-operative partnership.

Despite the afore-cited work where coordination was found as a driver towards more sustainable supply chains, a few papers identified settings where coordination can lead to higher emissions. Toptal and Cetinkaya (2017) observe numerically that, under cap-and-trade and carbon tax, coordinated solution may increase total supply chain emissions compared to decentralized solution. Bouchery, Ghaffari, Jemai, and Tan (2017) investigates the effect of supply chain coordination on supply chain cost and emissions. They identify sufficient conditions under which coordination may lead to higher emissions than decentralized, which involves order quantity being higher in the coordinated case than the decentralized case. Our research extends the above work in several ways. First, we consider a more general form of the buyer-vendor model. In contrast to the lot-for-lot setting discussed in the majority of the above papers, we study the general case where the supplier optimizes its own ordering decision. Second, we extend the work of Toptal and Cetinkaya (2017) and Bouchery et al. (2017) by identifying necessary and sufficient conditions for total emissions to be higher under emission responsibility sharing and we discuss potential remedies for this problem and evaluate their relative effectiveness. Moreover, our theoretic framework is supported by a detailed numerical example using realistic problem parameter values where we examine the extent to which emission reduction efforts by individual firms are successful in reducing overall emissions.

Finally, there is extensive literature from environmental economics that examines the optimal design of environmental policies from the perspective of a social planner (see for example Barnett, 1980; Baumol, 1972, and Katsoulacos & Xepapadeas, 1995). Results from this literature show that taxing emissions always increases abatement effort and reduces emissions. This literature does not account for the supply chain dynamics we model in this paper. In particular, it assumes that the abatement effort of one firm does not affect the cost of abatement of other firms.

3. A buyer-supplier model

We consider a buyer-supplier model of supply chain interactions that has been widely studied in the literature; see for example Jeuland and Shugan (1983), Lal and Staelin (1984), Weng (1995), Corbett and de Groote (2000), Cachon (2003), Cachon and Kok (2010) and the references therein. Specifically, we consider a serial supply chain consisting of a buyer (Firm 1) and a supplier (Firm 2). The buyer faces external demand, constant with a fixed rate (we discuss the case of endogenous demand later in the section and in Appendix C) and decides on the frequency with which to order from the supplier (or equivalently on the order quantities). In doing so, the buyer trades off fixed ordering costs with variable inventory holding costs. The supplier, in response to the orders from the buyer, decides similarly on the frequency of ordering from its own supplier (or on the frequency of producing internally) trading off fixed ordering (or production setup) costs with inventory holding costs. In other words, each firm faces an economic order quantity (EOQ) problem (Goyal, 1976; Harris, 1913).

Let D denote demand per unit time and p denote the unit selling price. The buyer incurs a fixed ordering cost A_1 per order, a holding cost h_1 per unit kept in inventory per unit time, and a

variable cost c_1 per unit purchased from the supplier in addition to the unit price w the supplier charges. The supplier incurs similar costs with corresponding parameters A_2 , h_2 , and c_2 , respectively. Without loss of generality, we assume that orders are delivered from the supplier to the buyer with zero leadtime and no safety inventory (a positive leadtime or safety stock can be included without affecting the solution of the problem). We also assume that each firm must always keep enough inventory to satisfy all the demand from its customers (the analysis can be easily extended to settings with backorders). It is possible to consider more general cost functions, including when cost parameters are non-linear or exhibit discontinuities. Section 5 demonstrates this treatment using a detailed numerical example. However, the qualitative insights we derive remain the same and we keep, consistent with much of the existing literature, the simpler form in order to illustrate the key tradeoffs and for the sake of tractability.

In addition to costs, there may be emissions associated with ordering, processing, and inventory holding. We let $\hat{A}_i$ denote the amount of emissions associated with each order placed by firm i (e.g., due to transportation or production setup), $\hat{h}_i$ the amount of emissions due to a unit held in inventory per unit time² (e.g., due to heating or refrigeration of stored inventory³), and $\hat{c}_i$ the amount of emissions per unit purchased or produced (e.g., due to energy consumed during transport, handling, and processing). Without loss of generality, we assume that A_i and $\hat{A}_i$ are independent of the order quantity. In fact, any quantity-dependent setup cost/emissions with a positive fixed portion can be included in the per unit cost/emissions in an equivalent formulation. We only require that these parameters be non-negative so that it is possible for some to be zero. For example, a firm may have negligible emissions associated with initiating orders, holding inventory, or with order processing. Similar to cost, it is possible to consider more general emission functions and the results we describe continue to hold when the emission parameters exhibit non-linearities; see Section 5 for an example of this treatment.

Similar to costs, characterizing emission parameters in practice requires a data collection and documentation effort. Fortunately, emission data is increasingly available on standard processes, including transportation and storage; see for example (Cachon, 2014), Chen, Benjaafar, and Elomri (2013) and Demir, Bektas, and Laporte (2014). There are also increasingly standards for measuring and reporting different categories of emissions, or so-called emission scopes. A prominent example of such a standard is the Greenhouse Gas Protocol (GHGP) developed by the World Resource Institute and the World Business Council for Sustainable Development. According to the GHGP, emissions are classified into scope 1, scope 2, and scope 3 emissions, with scope 1 referring to direct emissions by the firm at its installations, scope 2 to indirect emissions by the firm via usage of electricity, heat and steam, and scope 3 to indirect emissions not covered by scope 2 including those generated by activities outsourced in the firm's upstream and downstream supply chains (GHGP, 2011).

We consider a setting where each firm incurs a penalty at rate t per unit of emissions it emits (scope 1 and 2 emissions). As discussed in the introduction, the penalty can be self-imposed or externally mandated. In the case where the penalty is self-imposed, the rate t may correspond to the prevailing market price of offsets.

If it is externally mandated, it may correspond to a tax imposed by a regulating entity. It is possible to consider settings where the penalty rate is non-linear and varies with the amount of emissions. It is also possible to consider settings where only one of the firms incurs an emission penalty (e.g., the case where one firm chooses to offset its emissions but not the other) or where the emission penalties are different for different firms. In what follows, we treat the case where both firms are subject to the same penalty (e.g., both firms seek to be emission-neutral by purchasing offsets from the same offset market). However, the effects we describe are also present and may be more prominent in the more general settings mentioned above.

The objective of each firm is to maximize its own after-penalty profit by choosing an ordering quantity, q_i for firm $i = 1, 2$. Since demand and price are fixed, revenue is unaffected by the ordering decisions. We discuss later in the section and in Appendix C the implication of the firms making other decisions regarding the selling price, the wholesale price, and abatement efforts that could impact emission parameters. First, the buyer chooses its order quantity; then does the supplier, taking into account the ordering decision of the buyer. It is not difficult to show that in such a setting the optimal ordering policy is a *nested* policy with the supplier ordering an integer multiple m_2 of the buyer's order quantity q_1 (see for example Chapter 2 of Zipkin (2000)). Note that the buyer is unaffected by the decisions of the supplier but the reverse is not true. Table 1 summarizes the notation used throughout the paper.

The problem faced by the buyer can be formulated as

$$\max_{q_1} z_1(q_1) = (p - w - c_1)D - \frac{A_1 D}{q_1} - \frac{h_1 q_1}{2} - t \left(\frac{\hat{A}_1 D}{q_1} + \frac{\hat{h}_1 q_1}{2} + \hat{c}_1 D \right), \quad (1)$$

while the problem faced by the supplier, given that the buyer orders quantity q_1 , can be formulated as

$$\max_{m_2} z_2(m_2, q_1) = (w - c_2)D - \frac{A_2 D}{m_2 q_1} - \frac{h_2 (m_2 - 1) q_1}{2} - t \left(\frac{\hat{A}_2 D}{m_2 q_1} + \frac{\hat{h}_2 (m_2 - 1) q_1}{2} + \hat{c}_2 D \right), \quad (2)$$

where the second argument of the function z_2 is used to highlight the dependency of the profit function of the supplier on the decision of the buyer.

We let q_1^* denote the buyer's optimal order quantity and m_2^* the supplier's optimal order quantity multiplier. Also, let $\tilde{A}_i = A_i + t\hat{A}_i$ and $\tilde{h}_i = h_i + t\hat{h}_i$, for $i = 1, 2$, for notational convenience. Then, we can show that

$$q_1^* = \sqrt{\frac{2\tilde{A}_1 D}{\tilde{h}_1}}, \quad (3)$$

and m_2^* is an integer that satisfies the inequalities

$$m_2^* (m_2^* - 1) \leq \frac{\tilde{A}_2 \tilde{h}_1}{\tilde{A}_1 \tilde{h}_2} \leq m_2^* (m_2^* + 1). \quad (4)$$

Given order quantity q_1^* and order multiplier m_2^* , the buyer's and the supplier's emissions are respectively given by

$$e_1(q_1^*) = \frac{\hat{A}_1 D}{q_1^*} + \frac{\hat{h}_1 q_1^*}{2} + \hat{c}_1 D, \quad (5)$$

and

$$e_2(m_2^*, q_1^*) = \frac{\hat{A}_2 D}{m_2^* q_1^*} + \frac{\hat{h}_2 (m_2^* - 1) q_1^*}{2} + \hat{c}_2 D. \quad (6)$$

² The inventory space needed is proportional to the amount of inventory held. Inventory holding cost and emissions depend on the space required and are thus modeled as dependent to the inventory level.

³ Walmart's 2013 Global Responsibility Report (Walmart, 2013) states "refrigerants account for 13 percent of our total corporate greenhouse gas footprint, contributing nearly twice that of the fuel used in our trucks". This contribution is due to the leakage of refrigerants, potent greenhouse gases with global warming potentials that are thousands of times higher than that of carbon dioxide.

Table 1
Notation.

Parameter	Definition	Parameter	Definition
D	Demand per unit time	p	Buyer's unit selling price
w	Supplier's wholesale price	t	Unit emission penalty
A_i	Fixed cost of firm i	$\hat{A}_i$	Fixed emissions of firm i
$\hat{h}_i$	Firm i 's inventory holding emissions per unit per unit time	h_i	Firm i 's inventory holding cost per unit per unit time
$\tilde{A}_i$	$= A_i + t\hat{A}_i$	$\tilde{h}_i$	$= h_i + t\hat{h}_i$
$\hat{c}_i$	Variable cost per unit product purchased/produced by firm i	$\hat{c}_i$	Variable emissions per unit product purchased/produced by firm i
$\tilde{c}_i$	$= c_i + t\hat{c}_i$	q_i	Firm i 's order quantity
m_2	The integer multiple the supplier orders of the buyer's order quantity	$z_1(q_1)$	Buyer's after-penalty profit given its order quantity q_1
$z_2(m_2, q_1)$	Supplier's after-penalty profit for ordering integer multiple m_2 and the buyer's order quantity q_1	$e_1(q_1)$	Buyer's emissions given its order quantity q_1
$z_2(m_2, q_1)$	Supplier's emissions given the buyer's order quantity q_1 and its ordering integer multiple m_2	$z_{SC}(m_2, q_1)$	Total supply chain profit given the buyer's order quantity q_1 and the supplier's integer multiple m_2
$e_{SC}(m_2, q_1)$	Total supply chain emission given the buyer's order quantity q_1 and the supplier's ordering integer multiple m_2	α	The fraction of total supply chain emission allocated to the buyer under shared emission responsibility scheme
h'_2	$= (m_2 - 1)h_2$	A'_2	$= \frac{A_2}{m_2}$
$\hat{h}'_2$	$= (m_2 - 1)\hat{h}_2$	$\hat{A}'_2$	$= \frac{\hat{A}_2}{m_2}$
w_t	Gross weight of an empty freight truck	v	Total weight of a freight truck
n_i	Number of trucks needed in each delivery to firm i	$Fl(v)$	Fuel consumed per unit distance for truck weight v
a_j	$j = 1, 2, 3$; constants in the function $Fl(v)$	d_i	Transportation distance to firm i
f_t	Price per liter of fuel	$\hat{f}_t$	Emissions from consuming a liter of fuel
$S_i(q_i)$	Firm i 's after penalty fixed (transportation) cost given order size q_i	f_i^e	Firm i 's energy consumed to operate a unit of space per unit time
T	The buyer's voluntary emission reduction target	d	Constant in constant elasticity demand function
Θ_i	Size of firm i 's inventory space	β	Maximum amount of inventory held per unit space
c_i^f	Firm i 's rent per unit space per unit time	s	Driver wage per unit distance traveled
p_e	Unit cost of energy	$\hat{p}_e$	Emissions from consuming a unit of energy

Total supply chain profit and total supply chain emission can then be obtained respectively as

$$z_{SC}(m_2^*, q_1^*) = z_1(q_1^*) + z_2(m_2^*, q_1^*),$$

and

$$e_{SC}(m_2^*, q_1^*) = e_1(q_1^*) + e_2(m_2^*, q_1^*).$$

Let us first consider the case where the supplier uses a *lot-for-lot* policy (i.e., $m_2 = 1$). By virtue of inequalities (4), the lot-for-lot policy is optimal when $0 \leq \frac{\hat{A}_2 \hat{h}_1}{\hat{A}_1 \hat{h}_2} \leq 2$. The lot-for-lot policy is commonly used even when it is not optimal because of its simplicity and because it is consistent with the principle of just-in-time adopted by many firms; see for example (Corbett & de Groote, 2000). The results below apply regardless of whether the lot-for-lot policy is optimal or not.

Under a lot-for-lot policy, the expression of supplier's emissions simplifies to

$$e_2 = \hat{A}_2 \sqrt{\frac{\hat{h}_1 D}{2\hat{A}_1}} + \hat{c}_2 D, \quad (7)$$

and that of total supply chain emission to

$$e_{SC} = (\hat{A}_1 + \hat{A}_2) \sqrt{\frac{\hat{h}_1 D}{2\hat{A}_1}} + \hat{h}_1 \sqrt{\frac{\hat{A}_1 D}{2\hat{h}_1}} + (\hat{c}_1 + \hat{c}_2) D, \quad (8)$$

where, for ease of notation, we have dropped the argument $m_2 (= 1)$ and $q_1^* (= \sqrt{\frac{2\hat{A}_1 D}{\hat{h}_1}})$ from the notation of the emission functions.

In the following theorem, we characterize the effect of the emission penalty on total supply chain emission (the proof of the theorem and all other results in the paper are provided in Appendix A).

Theorem 1 (Lot-for-Lot). Higher emission penalties may not necessarily lead to lower total supply chain emission. In particular, under

the lot-for-lot policy, total supply chain emission e_{SC} is increasing in the emission penalty t if and only if $\frac{\hat{A}_1}{\hat{h}_1} \leq \frac{A_1}{h_1}$ and $\hat{A}_2 \geq \frac{\hat{h}_1 A_1 - h_1 \hat{A}_1}{\hat{h}_1}$. A sufficient condition, independent of t , for total supply chain emission to increase in the emission penalty is given by $\frac{\hat{A}_1}{\hat{h}_1} \leq \frac{A_1}{h_1}$ and $\hat{A}_2 \geq \frac{\hat{h}_1 A_1 - h_1 \hat{A}_1}{\hat{h}_1}$. If $\frac{\hat{A}_1}{\hat{h}_1} \leq \frac{A_1}{h_1}$ but $\hat{A}_2 < \frac{\hat{h}_1 A_1 - h_1 \hat{A}_1}{\hat{h}_1}$, then there exists a threshold t' on the emission penalty such that if $t \leq t'$, then total supply chain emission is decreasing in t and if $t > t'$, then total supply chain emission is increasing in t , with $t' = \frac{\hat{h}_1 A_1 - h_1 \hat{A}_2 - h_1 \hat{A}_1}{\hat{h}_1 \hat{A}_2}$.

The above results can be explained as follows. When $\frac{\hat{A}_1}{\hat{h}_1} \leq \frac{A_1}{h_1}$, the buyer's optimal order quantity q_1^* decreases with the emission penalty (the introduction of a penalty moves the buyer from the cost-optimal order quantity, given by $\sqrt{2A_1 D/h_1}$, in the direction of the emission-optimal order quantity, given by $\sqrt{2\hat{A}_1 D/\hat{h}_1}$). In doing so, the buyer of course reduces its own emissions. However, this comes at the expense of the supplier whose emissions increase. This is because, under lot-for-lot, the supplier uses the same order quantity as the buyer. The reduction in the order quantity leads the supplier to incur higher fixed emissions associated with more frequent ordering without benefiting from lower inventory-related emissions, as does the buyer (recall that, under lot-for-lot, the supplier does not keep any inventory). If the emission increase by the the supplier is higher than the emission reduction experienced by the buyer, then total supply chain emission sees a net increase. A condition for this to occur is for the supplier's emission parameter $\hat{A}_2$ to be larger than a threshold as specified by the condition in the theorem. Note that because this threshold is decreasing in t , it is possible for total emissions to decrease as t increases initially and then to increase as t increases further.

Higher emission penalties can also lead to higher total supply chain emission when the supplier does not use a lot-for-lot policy and instead uses a multiplier, other than one, of the buyer's order quantity (regardless of whether or not this multiplier is optimized). First, consider the case where the supplier uses an

exogenously specified multiplier m_2 ($m_2 \geq 1$). Let $A'_2 = \frac{A_2}{m_2}$, $h'_2 = (m_2 - 1)h_2$, $\hat{A}'_2 = \frac{\hat{A}_2}{m_2}$ and $\hat{h}'_2 = (m_2 - 1)\hat{h}_2$. Then the total supply chain profit and emissions can be rewritten, respectively, as follows:

$$z_{SC}(q_1^*, m_2) = pD - \left(\frac{(A_1 + A'_2)D}{q_1^*} + \frac{(h_1 + h'_2)q_1^*}{2} + (c_1 + c_2)D \right) - t \left(\frac{(\hat{A}_1 + \hat{A}'_2)D}{q_1^*} + \frac{(\hat{h}_1 + \hat{h}'_2)q_1^*}{2} + (\hat{c}_1 + \hat{c}_2)D \right), \quad (9)$$

and

$$e_{SC}(q_1^*, m_2) = \frac{(\hat{A}_1 + \hat{A}'_2)D}{q_1^*} + \frac{(\hat{h}_1 + \hat{h}'_2)q_1^*}{2} + (\hat{c}_1 + \hat{c}_2)D. \quad (10)$$

Note that when $m_2 > 1$, the supplier holds inventory and therefore incurs inventory holding costs and emissions.

The following lemma provides necessary and sufficient conditions for the total emissions to increase with the emission penalty given an exogenously specified multiplier m_2 , which will be used to derive conditions for the case where m_2 is chosen optimally.

Lemma 1 (Fixed m_2). Given multiplier m_2 , total supply chain emission increases with the emission penalty t if and only if one of the following conditions holds:

- $\frac{\hat{A}_1}{\hat{h}_1} \leq \frac{A_1}{h_1}$ and $\hat{A}'_2 \geq \frac{\hat{A}_1(\hat{h}_1 + \hat{h}'_2)}{\hat{h}_1} - \hat{A}_1$, or
- $\frac{\hat{A}_1}{\hat{h}_1} \geq \frac{A_1}{h_1}$ and $\hat{A}'_2 \leq \frac{\hat{A}_1(\hat{h}_1 + \hat{h}'_2)}{\hat{h}_1} - \hat{A}_1$.

This result generalizes that of Theorem 1 and can be explained as follows. When $\frac{\hat{A}_1}{\hat{h}_1} \leq \frac{A_1}{h_1}$, the buyer's optimal order quantity q_1^* decreases with the emission penalty, per the explanation given for the result in Theorem 1. This has again the effect of reducing the buyer's emissions but increasing the supplier's fixed emissions. When $\hat{A}'_2 \geq \frac{\hat{A}_1(\hat{h}_1 + \hat{h}'_2)}{\hat{h}_1} - \hat{A}_1$, the increase in the supplier's fixed emissions is sufficiently large to lead to a net increase in total supply chain emission. When $\frac{\hat{A}_1}{\hat{h}_1} \geq \frac{A_1}{h_1}$, the buyer reduces its emissions by increasing its optimal order quantity q_1^* . However, this has the effect of increasing the inventory-related emissions of the supplier. If $\hat{A}'_2 \leq \frac{\hat{A}_1(\hat{h}_1 + \hat{h}'_2)}{\hat{h}_1} - \hat{A}_1$, the increase in the supplier's inventory-related emissions is sufficiently large to lead to an increase in total supply chain emission. Note that when $m_2 = 1$ (the lot-for-lot case), only the first condition of Lemma 1 can hold. In that case, substituting for $m_2 = 1$ leads to the result in Theorem 1.

When m_2 is not fixed and is instead chosen optimally by the supplier, the optimal value m_2^* varies with the penalty rate t . The following theorem provides necessary and sufficient conditions for the total emissions to increase with the emission penalty in this case.

Theorem 2 (Optimal m_2). Let $\underline{m}_2 = \inf\{m_2 \mid m_2(m_2 - 1) \leq \frac{\hat{A}_2\hat{h}_1}{\hat{A}_1\hat{h}_2} \leq m_2(m_2 + 1), t \geq 0\}$, $\bar{m}_2 = \sup\{m_2 \mid m_2(m_2 - 1) \leq \frac{\hat{A}_2\hat{h}_1}{\hat{A}_1\hat{h}_2} \leq m_2(m_2 + 1), t \geq 0\}$, $S_t = \{t \mid \sqrt{\frac{\hat{A}_2\hat{h}_1}{\hat{A}_1\hat{h}_2}} = m_2, \underline{m}_2 \leq m_2 \leq \bar{m}_2, m_2 \in \mathbb{N}^+\}$,

and $t_1 < t_2 < \dots < t_n$, where n is the cardinality of set S_t and $t_i \in S_t$ for $i = 1, \dots, n$. Then, total supply chain emission increases with the emission penalty t if and only if one of the following conditions holds:

- $t < t_1$ or $t_i < t < t_{i+1}$ ($\forall i \in \{1, \dots, n-1\}$), $\frac{\hat{A}_1}{\hat{h}_1} \leq \frac{A_1}{h_1}$ and $\hat{A}'_2 \geq \frac{\hat{A}_1(\hat{h}_1 + \hat{h}'_2)}{\hat{h}_1} - \hat{A}_1$,
- $t < t_1$ or $t_i < t < t_{i+1}$ ($\forall i \in \{1, \dots, n-1\}$), $\frac{\hat{A}_1}{\hat{h}_1} \geq \frac{A_1}{h_1}$ and $\hat{A}'_2 \leq \frac{\hat{A}_1(\hat{h}_1 + \hat{h}'_2)}{\hat{h}_1} - \hat{A}_1$,

- $\frac{\hat{A}_2\hat{h}_1 + \hat{A}_2\hat{h}_1}{\hat{A}_1\hat{h}_2 + \hat{A}_1\hat{h}_2} \Big|_{t=t_i} \leq \frac{\hat{A}_2\hat{h}_1}{\hat{A}_1\hat{h}_2} \Big|_{t=t_i}$ and $m_2^*(t_i)(m_2^*(t_i) + 1) \geq \frac{\hat{A}_2\hat{h}_1}{\hat{A}_1\hat{h}_2} \Big|_{t=t_i}$ ($\forall i \in \{1, \dots, n\}$),
- $\frac{\hat{A}_2\hat{h}_1 + \hat{A}_2\hat{h}_1}{\hat{A}_1\hat{h}_2 + \hat{A}_1\hat{h}_2} \Big|_{t=t_i} \geq \frac{\hat{A}_2\hat{h}_1}{\hat{A}_1\hat{h}_2} \Big|_{t=t_i}$ and $m_2^*(t_i)(m_2^*(t_i) + 1) \leq \frac{\hat{A}_2\hat{h}_1}{\hat{A}_1\hat{h}_2} \Big|_{t=t_i}$ ($\forall i \in \{1, \dots, n\}$),

where $m_2^*(t_i)$ is given by (4) at $t = t_i$.

Corollary 1. $\forall i \in \{1, \dots, n\}$, the supply chain emission increases at t_i if one of the following two conditions holds:

- $\frac{\hat{A}_2}{\hat{h}_2} \leq \frac{A_2}{h_2}$ and $\frac{\hat{A}_2\hat{h}_1 + \hat{A}_2\hat{h}_1}{\hat{A}_1\hat{h}_2 + \hat{A}_1\hat{h}_2} \Big|_{t=t_i} \geq \frac{\hat{A}_2\hat{h}_1}{\hat{A}_1\hat{h}_2} \Big|_{t=t_i}$,
- $\frac{\hat{A}_2}{\hat{h}_2} \geq \frac{A_2}{h_2}$ and $\frac{\hat{A}_2\hat{h}_1 + \hat{A}_2\hat{h}_1}{\hat{A}_1\hat{h}_2 + \hat{A}_1\hat{h}_2} \Big|_{t=t_i} \leq \frac{\hat{A}_2\hat{h}_1}{\hat{A}_1\hat{h}_2} \Big|_{t=t_i}$.

Theorem 2 and Corollary 1 suggests that when the supplier chooses the integer multiple m_2^* , it is possible for the supplier's decision to lead to higher total supply chain emission in some cases. Specifically, this occurs when the supplier's optimal order quantity, i.e., $m_2^*q_1^*$, decreases (increases) with the emission penalty, however, the supplier chooses a larger (smaller) integer multiple m_2^* in response to the penalty increase because the buyer's order quantity decreases (increases) at a faster rate than that of the supplier. Due to the integrality of m_2^* , this increase overwhelms any emission decrease as a result of the buyer's decision. Fig. 1 uses two examples with hypothetical parameter values to illustrate two possible ways in which the supply chain emission increase with the emission penalty. In Fig. 1(a), the emission increases with penalty in regions where m_2^* is fixed due to the buyer's decision q_1^* , and decreases when m_2^* changes value (this corresponds to the sharp drops in Fig. 1(a)). In Fig. 1(b), the emission decreases with penalty in regions where m_2^* is fixed, while it increases at $t = 0.515$ where m_2^* increases from 2 to 3.

We note that the conditions in Theorems 1, 2 and Corollary 1 readily apply to the system with a positive safety stock. To see that, let the buyer's safety stock be $ss = \gamma \frac{q_1}{2}$, where γ is a constant of arbitrary value. For example, if 20% of the buyer's average inventory ($\frac{q_1}{2} + ss$) is safety inventory, then $\gamma = 0.25$. Then, the buyer's problem becomes

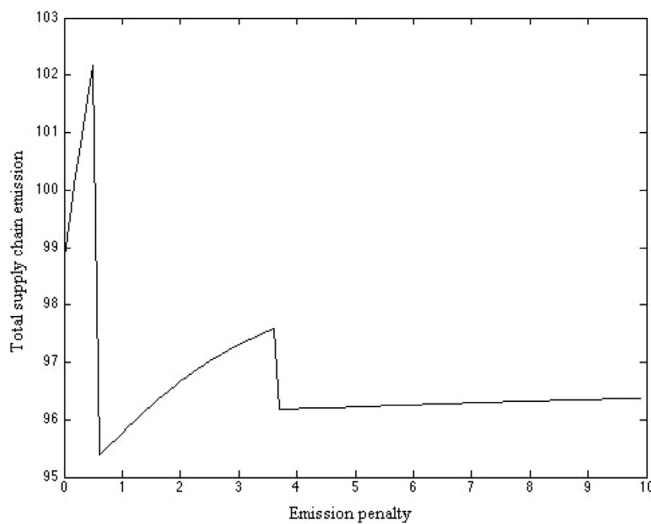
$$\max_{q_1} z_1(q_1) = (p - w - c_1)D - \frac{A_1D}{q_1} - \frac{h_1(1 + \gamma)q_1}{2} - t \left(\frac{\hat{A}_1D}{q_1} + \frac{\hat{h}_1(1 + \gamma)q_1}{2} + \hat{c}_1D \right).$$

It is easy to see that this scenario is equivalent to systems (1) and (2) with unit inventory cost (emissions) $(1 + \gamma)h_1$ ($(1 + \gamma)\hat{h}_1$). Therefore, it is straightforward to check that the conditions in Theorems 1, 2 and Corollary 1 and the corresponding insights continue to hold regardless of whether and how much safety stock is held. For ease of exposition, we continue to derive analytical results under the no safety stock assumption. We consider the effect of safety stock in a numerical example in Section 5, where we examine to what extent the conditions in Theorems 1 and 2 can hold in practice using realistic problem parameter values.

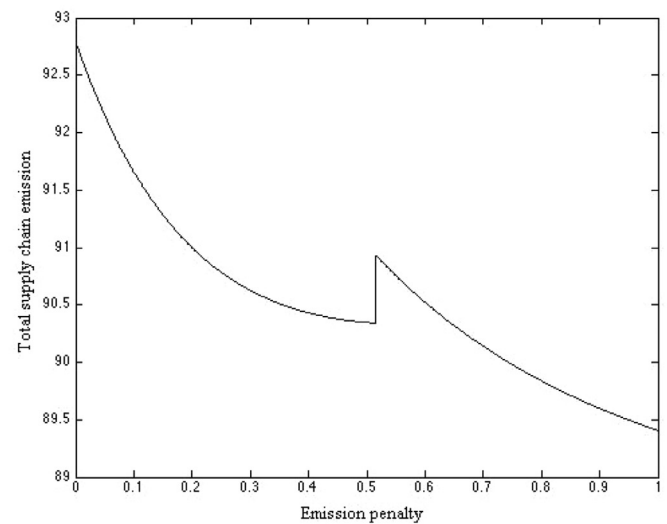
We conclude this section by making the following remarks.

Remark 1. Our analysis can be readily extended to serial supply chains with multiple firms, where each firm, other than the end buyer, is a supplier to the one directly downstream from it. We can show that, if the conditions in Theorems 1 and 2 hold, the potential negative impact of higher emission penalties continues to be present and in fact can be amplified. For example, in the case where all suppliers are symmetric in their parameters and all employ a lot-for-lot policy, total supply chain emission increases linearly in the number of firms if the conditions in Theorem 1 hold.

Remark 2. Although we have considered settings where firms are subject to the same emission penalty, the potential negative



(a) $A_1 = 5, A_2 = 10, h_1 = 1.5, h_2 = 1, \hat{A}_1 = 3, \hat{A}_2 = 25, \hat{h}_1 = 2, \hat{h}_2 = 1, D = 100$



(b) $A_1 = 5, A_2 = 10, h_1 = 2, h_2 = 1, \hat{A}_1 = 3, \hat{A}_2 = 10, \hat{h}_1 = 4, \hat{h}_2 = 1.1, D = 100$

Fig. 1. The impact of the emission penalty on total supply chain emission under optimal m_2 .

impact of higher emission penalties is also present when the penalties faced by the firms are different or when only the buyer faces a penalty (e.g., this is easy to verify in the case of lot-for-lot policy). More significantly, this effect is present when neither firm is subject to an emission penalty but instead the buyer decides to voluntarily reduce its own emissions by a specified amount (i.e., the buyer maximizes its profit subject to a constraint on emissions). In this case, we can find conditions similar to those of Theorems 1 and 2 involving the emission reduction target, with higher percentage reduction targets leading to higher total supply chain emission (see Appendix B for details).

Remark 3. We have assumed so far that both selling and wholesale prices are fixed. Although this may be a reasonable assumption over the short term, over the long term, both the buyer and the supplier are likely to adjust their prices in response to the increase in their cost structure due to the emission penalties. In Appendix C, we discuss the implication of having firms decide jointly on price and order quantity in a setting where demand is decreasing in price. We show that higher emission penalties lead the buyer to charge higher prices. In turn, this leads to a reduction in demand. This reduction in demand obviously reduces emissions. We show that whether or not this *curtailment* in demand is sufficient to result in a net decrease in total supply chain emission depends on the price sensitivity of demand. In particular, if price sensitivity is sufficiently low, then it continues to be possible for higher penalties to lead to higher emissions.

Remark 4. We have implicitly assumed that participation constraints for both the buyer and the supplier are satisfied. That is, the selling price p and the wholesale price w are sufficiently high for both the buyer and the supplier to realize positive profits. For example, in the lot-for-lot case, this is equivalent to requiring that $p \geq w + \tilde{c}_1 + \sqrt{\frac{2\tilde{A}_1\tilde{h}_1}{D}}$ and $w \geq \tilde{A}_2\sqrt{\frac{\tilde{h}_1}{2\tilde{A}_1D}} + \tilde{c}_2$.

Remark 5. We have assumed that the emission parameters are exogenously specified. Again, this is a reasonable assumption over the short term. Over the long term, firms may decide to exert costly effort to reduce their emission intensity (e.g., switch to renewable sources of energy or invest in more energy-efficient equipment). A reduction in the intensity of fixed emissions or in

the emissions related to inventory storage may or may not mitigate the possibility of higher penalties leading to more emissions. For example, the buyer may decide to reduce its fixed emissions, leading it to order even more frequently. If this is not matched by similar emission reductions by the supplier, then the net effect could be even higher total supply chain emission than without any emission intensity reduction on the part of the buyer.

4. Remedies

In order to prevent emission penalties from backfiring (i.e., higher penalties leading to higher total supply chain emission and not less), a remedy scheme would naturally require that the buyer internalizes either partially or fully the cost of the externality it imposes on the supplier. A simple scheme would consist of penalizing the firms for a fraction of total supply chain emission instead of penalizing them for only their own emissions. Such a scheme has been widely discussed in the literature (see, for example, Caro et al., 2013; Gopalakrishnan et al., 2016 and the references therein) and is consistent with the Green House Gas Protocol's recent guidelines of accounting for Scope 3 emissions (GHGP, 2011). It is also consistent with voluntary efforts of certain firms to reduce emissions of their entire supply chain, including the emissions of both their suppliers and their customers. For example, General Mills and PepsiCo have recently set specific targets for reducing their Scope 3 emissions (Science Based Targets, n.d.).

The implementation of the emission responsibility sharing scheme requires substantial collaboration and information sharing between parties within and outside of the supply chain. Specifically, it may be enforced in the following settings. First, it may be enforced through government policy aided by third-party audits/verifications. Second, it may be enforced if the buyer and supplier are business units within the same firm, e.g., the internal carbon taxes at Microsoft and Disney (Davenport, 2013; DiCaprio, 2013). Third, it may be enforced by a buyer/supplier who is the dominant leader of its supply chain. For example, Walmart has been assessing its supply chain emissions since 2007 and engaging its suppliers in emission reduction efforts. Furthermore, the practice of emission information sharing has been growing over the past few years. For example, CDP's Supply Chain Program pro-

vide support to various buyers in collecting emission related data from their suppliers and engaging suppliers in emission reducing activities.

Other simple schemes would involve enforcing supply chain coordination, or penalizing consumption instead of production (see Appendices C and D for detailed discussion). The latter would of course be effective only in settings where demand is sensitive to pricing as we discuss in Appendix C. Below we briefly discuss the implications of these schemes.

Consider first the scheme where the buyer is penalized for a fraction $\alpha \in [0, 1]$ of total supply chain emission, while the supplier is penalized for a fraction $1 - \alpha$ of total supply chain emission. We refer to such a scheme as *shared emission responsibility*. Given penalty t and emission allocation α , the buyer's problem under shared emission responsibility is

$$\max_{q_1 \geq 0} z_1(q_1, m_2) = (p - w)D - \left(\frac{A_1 D}{q_1} + \frac{h_1 q_1}{2} + c_1 D \right) - \alpha t \left(\frac{(\hat{A}_1 + \hat{A}_2/m_2)D}{q_1} + \frac{(\hat{h}_1 + (m_2 - 1)\hat{h}_2)q_1}{2} + (\hat{c}_1 + \hat{c}_2)D \right), \quad (11)$$

while the supplier's problem is given by

$$\max_{m_2 \in \mathbb{N}^+} z_2(q_1, m_2) = (w - c_2)D - \left(\frac{A_2 D}{m_2 q_1} + \frac{h_2(m_2 - 1)q_1}{2} \right) - (1 - \alpha)t \left(\frac{(\hat{A}_1 + \hat{A}_2/m_2)D}{q_1} + \frac{(\hat{h}_1 + (m_2 - 1)\hat{h}_2)q_1}{2} + (\hat{c}_1 + \hat{c}_2)D \right). \quad (12)$$

Theorem 3. Supply chain emission is always decreasing in the emission penalty t under the shared emission responsibility scheme.

Theorem 3 shows that the shared emission responsibility scheme indeed guarantees that total supply chain emission is always decreasing in the emission penalty t . This seems to suggest that shared emission responsibility should always be applied in order to guarantee emission reduction. However, such a conclusion can only be drawn if shared emission responsibility results in total supply chain emission that are lower than those obtained under individual responsibility (i.e., total supply chain emission when each firm is penalized for only its own emissions). In the following, we show that this is not always the case. In fact, it is possible to end up with more emissions when there is shared responsibility than when there is not. For ease of exposition, we show this point for when the supplier uses a lot-for-lot policy. Under lot-for-lot, the buyer's problem can be simplified as

$$\max_{q_1 \geq 0} z_1(q_1) = (p - w)D - \left(\frac{A_1 D}{q_1} + \frac{h_1 q_1}{2} + c_1 D \right) - \alpha t \left(\frac{(\hat{A}_1 + \hat{A}_2)D}{q_1} + \frac{\hat{h}_1 q_1}{2} + (\hat{c}_1 + \hat{c}_2)D \right), \quad (13)$$

with a corresponding optimal order quantity given by $q_1^*(\alpha) = \sqrt{\frac{2[A_1 + \alpha t(\hat{A}_1 + \hat{A}_2)]D}{h_1 + \alpha t \hat{h}_1}}$. Given $q_1^*(\alpha)$, the supplier's profit is given by

$$z_2(q_1^*(\alpha)) = wD - \left(\frac{A_2 D}{q_1^*(\alpha)} + c_2 D \right) - (1 - \alpha)t \left(\frac{(\hat{A}_1 + \hat{A}_2)D}{q_1^*(\alpha)} + \frac{\hat{h}_1 q_1^*(\alpha)}{2} + (\hat{c}_1 + \hat{c}_2)D \right). \quad (14)$$

Theorem 4. Given a penalty t , the shared emission responsibility scheme leads to strictly higher total supply chain emission than those

under no emission responsibility sharing under the lot-for-lot policy if and only if one of the following conditions holds:

- $\frac{\hat{A}_1 + \hat{A}_2}{\hat{h}_1} > \frac{\hat{A}_1}{\hat{h}_1}, \frac{\hat{A}_1}{\hat{h}_1} > \frac{A_1}{h_1}$, and $\alpha < \alpha_1$,
- $\frac{\hat{A}_1 + \hat{A}_2}{\hat{h}_1} < \frac{\hat{A}_1}{\hat{h}_1}, \frac{\hat{A}_1}{\hat{h}_1} < \frac{A_1}{h_1}, \frac{A_1}{h_1} \frac{\hat{A}_1}{\hat{h}_1} \geq \left(\frac{\hat{A}_1 + \hat{A}_2}{\hat{h}_1} \right)^2$, and $\alpha < \alpha_1$,
- $\frac{\hat{A}_1 + \hat{A}_2}{\hat{h}_1} > \frac{\hat{A}_1}{\hat{h}_1}, \frac{\hat{A}_1}{\hat{h}_1} \leq \frac{A_1}{h_1}, \frac{A_1}{h_1} \frac{\hat{A}_1}{\hat{h}_1} > \left(\frac{\hat{A}_1 + \hat{A}_2}{\hat{h}_1} \right)^2$, and $\alpha < \alpha_2$,
- $\frac{\hat{A}_1 + \hat{A}_2}{\hat{h}_1} < \frac{\hat{A}_1}{\hat{h}_1}, \frac{\hat{A}_1}{\hat{h}_1} \geq \frac{A_1}{h_1}, \frac{A_1}{h_1} \frac{\hat{A}_1}{\hat{h}_1} < \left(\frac{\hat{A}_1 + \hat{A}_2}{\hat{h}_1} \right)^2$, and $\alpha < \alpha_2$,
- $\frac{\hat{A}_1 + \hat{A}_2}{\hat{h}_1} < \frac{\hat{A}_1}{\hat{h}_1}, \frac{\hat{A}_1}{\hat{h}_1} < \frac{A_1}{h_1}, \frac{A_1}{h_1} \frac{\hat{A}_1}{\hat{h}_1} < \left(\frac{\hat{A}_1 + \hat{A}_2}{\hat{h}_1} \right)^2$, and $\min\{\alpha_1, \alpha_2\} < \alpha < \max\{\alpha_1, \alpha_2\}$,

$$\text{where } \alpha \in [0, 1], \alpha_1 = \frac{\frac{\hat{A}_1}{\hat{h}_1} - \frac{A_1}{h_1}}{\frac{\hat{A}_1 + \hat{A}_2}{\hat{h}_1} - \frac{\hat{A}_1}{\hat{h}_1}} \text{ and } \alpha_2 = \frac{h_1 \left[\frac{A_1}{h_1} \frac{\hat{A}_1}{\hat{h}_1} - \left(\frac{\hat{A}_1 + \hat{A}_2}{\hat{h}_1} \right)^2 \right]}{t(\hat{A}_1 + \hat{A}_2) \left(\frac{\hat{A}_1 + \hat{A}_2}{\hat{h}_1} - \frac{\hat{A}_1}{\hat{h}_1} \right)}.$$

As we can see from the above result, the choice of α affects the effectiveness of shared emission responsibility relative to individual responsibility (A commonly discussed scheme in the literature, mostly because of its perceived fairness, is one where α_i is chosen to correspond to the proportion of emissions for which firm i is responsible prior to the imposition of any penalties – i.e., in the business-as-usual case.). However, shared emission responsibility may be less effective than individual responsibility even if α is chosen so that total supply chain emission is minimized (i.e., $\alpha = 1$). This scenario would occur, for example, if $\frac{A_1}{h_1} > \frac{\hat{A}_1 + \hat{A}_2}{\hat{h}_1}$ and the emission penalty is relatively low under the lot-for-lot policy. This is because when $\frac{A_1}{h_1} > \frac{\hat{A}_1 + \hat{A}_2}{\hat{h}_1}$, the shared emission responsibility scheme leads to a higher order quantity than the one under no emission responsibility sharing. This results in lower fixed emissions for both the buyer and the supplier but higher inventory-related emissions for the buyer (recall that the supplier does not carry any inventory under the lot-for-lot policy). When the emission penalty is low, the decrease in the fixed emissions is less than the increase in the buyer's inventory-related emissions, and total supply chain emission would thus see a net increase under the shared emission responsibility scheme.

The above result reveals the limitation of a sharing scheme that relies on a single parameter because such a scheme does not allow for differentiating between the emissions of the two firms. That is, each firm is penalized for the same fraction of its own emissions and of the emissions of the other firm. A more general scheme for assigning emission responsibility would assign a fraction α_{ij} of the emission of firm j to firm i . Under such a scheme, individual responsibility is the special case where $\alpha_{ij} = 1$ for $i = j$ and $\alpha_{ij} = 0$ otherwise. Therefore, this scheme would be able to guarantee that shared emission responsibility leads to equal or lower emissions than individual responsibility. However, such a scheme could be challenging to implement in practice due to the level of information sharing required.

These results highlight the challenge of designing schemes for sharing emission responsibility and the difficulty in guaranteeing that such schemes would outperform ones based on individual responsibility. In fact, in Appendix D, we study the effect of fully coordinating the supply chain through a central planner under the lot-for-lot policy. We show that, consistent with Bouchery et al. (2017) and Toptal and Cetinkaya (2017), fully coordinating a supply chain may result in both higher cost and higher emissions than assigning individual responsibilities to each firm. We also note that the α value is treated as an exogenous parameter in this section, whereas its value may be selected to optimize certain objectives, e.g., profit, emissions. In Appendix E, we investigate the effect of an endogenous α under the lot-for-lot policy, where α is chosen (1) to maximize supply chain profit, (2) to minimize total supply

chain emission, and (3) to keep the proportion of emissions shared among firms constant. We show that sharing emission responsibility can lead to higher emissions than those under individual responsibility under all three schemes.

One can also consider a scheme where consumers are subject to a penalty t based on the embodied total supply chain emission for the product they buy. Such a penalty (a so-called *additive tax*) increases the effective price the consumer pays for the product. In settings where consumer demand is sensitive to price, such a tax would lead to lower demand with everything else remaining the same. In Appendix C, we show that such a scheme results in similar outcomes in terms of emissions as one that penalizes the buyer for the entire total supply chain emission (i.e., shared emission responsibility with $\alpha = 1$). Again, as discussed above, such a scheme may not always result in lower total supply chain emission than with individual emission responsibility.

5. A numerical example

In this section, we examine the extent to which emission penalties may or may not be effective in reducing total supply chain emission when (a) more detailed models are used to estimate the cost and emission functions and (b) the model parameters are calibrated using realistic values. We do so by providing detailed numerical analysis of a supply chain consisting of two firms, a supplier and a wholesaler. The wholesaler sources a single product (or a fixed assortment of products) from the supplier who, in turn, secures supply from an outside source.

As the model in Section 3 suggests, each firm incurs fixed costs and emissions associated with initiating an order, and costs and emissions associated with keeping inventory. We assume that, for both the supplier and the wholesaler, fixed costs and fixed emissions are mostly due to trucking. In particular, transportation costs are determined by the cost of fuel and the wages of drivers. Transportation emissions are determined by the amount of fuel consumed (a function of the weight of the load and the distance traveled) and the emission-intensity of the fuel. Specifically, we assume that the fuel consumed per unit distance can be approximated as follows (based on data reported by Franzese & Davidson (2011))⁴:

$$Fl(v) = a_1 v^2 + a_2 v + a_3,$$

where $Fl(v)$ is the fuel consumed per unit distance (in liters), v is the weight of the truck (the sum of the weight of the empty truck and that of the carried load), $a_1 = 8.543 \times 10^{-11}$, $a_2 = -1.168 \times 10^{-6}$, and $a_3 = 0.2497$ are parameters that have been calibrated empirically.

Without loss of generality, we scale the unit product weight to 1 kilogram. Assuming the capacity of a truck is 80,000 pounds (1b) or 36,287 kilograms (truckersreport, 2013), we let n_1 be the smallest integer such that $36,287n_1 \geq q_1$ (recall that q_1 is the wholesaler's order quantity). Then, each order from the wholesaler would require the deployment of n_1 trucks. Assuming the load is equally allocated among the n_1 trucks, the weight of the load carried in each truck is given by $v = \frac{q_1}{n_1} + w_t$, where w_t is the weight of an empty truck.

The transportation cost incurred by the wholesaler for each order placed can then be computed as $n_1[a_1(\frac{q_1}{n_1} + w_t)^2 + a_2(\frac{q_1}{n_1} +$

$w_t) + a_3]f_t d_1 + n_1 s d_1$ while emissions can be computed as $n_1[a_1(\frac{q_1}{n_1} + w_t)^2 + a_2(\frac{q_1}{n_1} + w_t) + a_3]\hat{f}_t d_1$, where f_t is the unit price of diesel fuel, $\hat{f}_t$ is the amount of emissions per unit of diesel consumed, and s is the wage of a driver per unit distance driven.

We assume that inventory-related costs are primarily determined by space rental costs (i.e., the rental cost of a warehouse) and the cost of utilities. We assume that inventory-related emissions are primarily determined by the energy consumed during the operation of the warehouses. Note that we consider also the impact of firm i 's safety stock $ss_i = \gamma_i \frac{q_i}{2}$ in this example, where γ_i is the ratio between safety stock and cycle stock. The size of firm i 's storage space Θ_i is proportional to the maximum amount of inventory held $((1 + \frac{\gamma_i}{2})q_i)$, and we let $\Theta_i = (1 + \frac{\gamma_i}{2})q_i/\beta$ where β denotes the maximum amount of inventory held per unit of storage space (see Cachon, 2014 for a detailed discussion and justification). Therefore, the space rental cost and the amount of energy consumed are proportional to q_i with firm i 's inventory-related cost and emissions per unit time being $\frac{h_i}{2}q_i$ and $\frac{\hat{h}_i}{2}q_i$ respectively. In particular, $\frac{h_i}{2} = (1 + \frac{\gamma_i}{2})(\frac{c_i^r + f_i^e p_e}{\beta} + \frac{\tau_i c_i}{2})$ and $\frac{\hat{h}_i}{2} = (1 + \frac{\gamma_i}{2})\frac{f_i^e \hat{p}_e}{\beta}$, where c_i^r is the rent per unit space per unit time, f_i^e is the energy consumed to operate a unit of space per unit time, τ_i is firm i 's interest rate, p_e is the unit cost of energy, and $\hat{p}_e$ is the emissions from consuming a unit of energy.

The wholesaler's problem can now be restated as $(f_t + t\hat{f}_t)$ is denoted as $\tilde{f}_t$ for ease of exposition)

$$\begin{aligned} \min_{n_1 \in \mathbb{N}^+, q_1 > 0} \quad & z_1(n_1, q_1) = (\tilde{h}_1 + \frac{2a_1 \tilde{f}_t d_1 D}{n_1}) \frac{q_1}{2} \\ & + \frac{n_1[(a_1 w_t^2 + a_2 w_t + a_3)\tilde{f}_t d_1 + s d_1]D}{q_1} \\ & + [(2a_1 w_t + a_2)\tilde{f}_t d_1 + \tilde{c}_1]D \\ \text{s.t.} \quad & w_t(n_1 - 1) < q_1 \leq w_t n_1. \end{aligned} \quad (15)$$

We assume that $z_1(n_1, w_t(n_1 - 1) + 1) \geq z_1(n_1 - 1, w_t(n_1 - 1))$. This is not a restricting assumption and holds as long as it is more cost efficient to reduce the order size by 1 when the order size is just 1 unit over the current total capacity of the trucks. The supplier operates under lot-for-lot. Therefore, $q_2 = q_1^*$ and $n_2 = n_1^*$. Using Theorem 1, we derive the following corollary, which provides sufficient conditions for the total supply chain emissions to increase with the emission penalty in this example.

Corollary 2. The total supply chain emission increases in the emission penalty t if

$$d_2 \geq d_1 \left[\frac{f_t}{\hat{f}_t} + \frac{s}{(a_1 w_t^2 + a_2 w_t + a_3)\hat{f}_t} - \frac{h_1 + \frac{2a_1 f_t d_1 D}{n_1}}{\hat{h}_1 + \frac{2a_1 \hat{f}_t d_1 D}{n_1}} \right],$$

and one of the following conditions holds:

- $\frac{\hat{h}_1}{h_1} \geq \frac{\hat{f}_t}{f_t}$ and $1 < n_0 < \max\left\{1, \frac{1}{\hat{h}_1} \left[\left(\frac{w_t(\tilde{h}_1 + 2a_1 \tilde{f}_t d_1 D) + [(a_1 w_t^2 + a_2 w_t + a_3)\tilde{f}_t d_1 + s d_1]D}{\sqrt{2[(a_1 w_t^2 + a_2 w_t + a_3)\tilde{f}_t d_1 + s d_1]D}} \right)^2 - 2a_1 \tilde{f}_t d_1 D \right] \right\}$,
- $\frac{\hat{h}_1}{h_1} < \frac{\hat{f}_t}{f_t}$, $s \geq \frac{h_1 + \frac{2a_1 f_t d_1 D}{n_0}}{\hat{h}_1 + \frac{2a_1 \hat{f}_t d_1 D}{n_0}} (a_1 w_t^2 + a_2 w_t + a_3)\hat{f}_t - (a_1 w_t^2 + a_2 w_t + a_3)f_t$ and $1 < n_0 < \max\left\{1, \frac{1}{\hat{h}_1} \left[\left(\frac{w_t(\tilde{h}_1 + 2a_1 \tilde{f}_t d_1 D) + [(a_1 w_t^2 + a_2 w_t + a_3)\tilde{f}_t d_1 + s d_1]D}{\sqrt{2[(a_1 w_t^2 + a_2 w_t + a_3)\tilde{f}_t d_1 + s d_1]D}} \right)^2 - 2a_1 \tilde{f}_t d_1 D \right] \right\}$,

⁴ Franzese and Davidson (2011) report data collected for six Class-8 trucks over the course of one year at a rate of 5 readings per second. Truck weight and fuel consumption data of trucks traveling at around 65 miles per hour and on flat terrain from their study are fitted in the fuel consumption model in our paper. Regression was done for aggregated average weight and average fuel consumption for 6 weight ranges between 20,000 pounds and 80,000 pounds provided in Table 7 in Franzese and Davidson (2011). R-squared of the regression model is 0.9359 suggesting reasonable goodness of fit.

Table 2
Parameter values in the baseline scenario.

Parameter	Description	Value
h_1	Wholesaler's inventory cost per unit per unit time	\$1.028 kilograms per year
h_2	Supplier's inventory cost per unit per unit time	\$1.003 kilograms per year
$\hat{h}_1$	Wholesaler's inventory emissions per unit per unit time	1.699 kgCO ₂ kilograms per year
$\hat{h}_2$	Supplier's inventory emissions per unit per unit time	1.699 kgCO ₂ kilograms per year
f_t	Cost per unit energy consumed	\$0.715 l ⁻¹
$\hat{f}_t$	Emissions per unit energy consumed	2.669 kgCO ₂ l ⁻²
$\hat{c}_1$	Emissions per order processed by the wholesaler	0 kgCO ₂
$\hat{c}_2$	Emissions per order processed by the supplier	0 kgCO ₂
d_1	Transportation distance to the wholesaler	400 kilometers
d_2	Transportation distance to the supplier	400 kilometers
w_t	Truck gross weight	13, 608 kilograms
D	Demand rate	1.65×10^7 kilograms per year
s	Driver wage	\$0.484 per kilometer

- $\frac{\hat{h}_1}{h_1} \geq \frac{\hat{f}_t}{f_t}$ and $n_0 \leq 1$, or
- $\frac{\hat{h}_1}{h_1} < \frac{\hat{f}_t}{f_t}$, $s \geq \frac{h_1 + 2a_1 f_t d_1 D}{\hat{h}_1 + 2a_1 \hat{f}_t d_1 D} (a_1 w_t^2 + a_2 w_t + a_3) \hat{f}_t - (a_1 w_t^2 + a_2 w_t + a_3) f_t$ and $n_0 \leq 1$,

$$\text{where } n_0 = \left\lceil \frac{2[(a_2 w_t + a_3) \hat{f}_t d_1 + s d_1] D}{\hat{h}_1 w_t^2} - 1 \right\rceil.$$

We examine next whether the conditions specified in [Corollary 2](#) could arise when the parameters are calibrated using realistic values. Let us first consider the costs and emissions associated with holding inventory at the wholesaler. We use the estimates from [Cachon \(2014\)](#) of an average of 141 kilograms of inventory per square meter of inventory space (i.e., $\frac{(1+\gamma/2)q_1/2}{\Theta_1} = \frac{\beta}{2} = 141$ kilograms per square meter) and utility cost (from electricity and natural gas) of \$22.85 per square meter per year. For rental cost, we use the 2018 1st quarter average US rent for warehouse and distribution of \$5.5 per square feet per year (source: [www.statista.com](#)), or equivalently \$59.2 per square meter per year. Another component of inventory cost is the capital cost of inventory. We estimate this cost using the US average price of Navel oranges in April 2017 of \$1.174 per pound (Source: Bureau of Labor Statistics) and Walmart's second quarter gross margin of 25.4%, yielding $\$1.174 \times (1 - 0.254)$ per pound = \$1.93 per kilogram. The wholesaler's gross profit margin is estimated as Costco's second quarter gross profit margin in 2017, that is, 13.84% (source: [www.ycharts.com](#)). The wholesaler has an annual interest rate of 20%. 20% of the wholesaler's average inventory is safety stock, that is, $\gamma = 0.2/0.8 = 0.25$. Putting it all together leads to an estimate of $h_1 = (1 + \frac{0.25}{2}) [\frac{2(59.2 + 22.85)}{2 \times 141} + 0.2 \times 1.93 \times (1 - 0.1384)] = \$1.028$ per kilogram per year. For emissions, we use the estimate by [Walmart \(2014\)](#) of 19.8 kilograms of CO₂ emissions per square foot of retail space in year 2012 (or equivalently 213.13 kilograms of CO₂ per square meter per year). This leads to an estimate of $\hat{h}_1 = (1 + \frac{0.25}{2}) \frac{2 \times 213.13}{141 \times 2} = 1.699$ kilograms of CO₂ per kilogram per year.⁵

Next, let us consider the costs and emissions associated with transportation by the wholesaler. For the price of fuel, we use the 2015 US average diesel price of \$2.707 per gallon or \$0.715 per liter ([http://www.eia.gov/petroleum/gasdiesel/](#)). For emissions, we use US Environmental Protection Agency (EPA) estimate of 2.669 kilograms of CO₂ per liter of diesel ([EPA, 2005](#)). We assume the gross weight of the truck is 30,000 pounds or 13,608 kilograms. The distance travelled from supplier to wholesaler is assumed to be 400 kilometers. Drivers' wages are determined using an esti-

mated salary of \$50, 000 per year for 100,000 miles of driving, or equivalently \$0.484 per kilometers of driving.

The total annual demand is estimated using Walmart's 2016 aggregate sales of oranges of 1.527×10^9 pounds. Distributing the total demand over 42 regional distribution centers gives us the estimate for wholesaler's demand, that is, $1.527 \times 10^9 / 42$ pounds per year⁻¹ = 1.65×10^7 kilograms per year. Finally, we assume that other emissions associated with the wholesaler's handling and processing of ordered units is negligible. That is, we assume $\hat{c}_1 = 0$ (note that positive $\hat{c}_1$ may affect the percentage increase/decrease in emissions but not the overall trend).

For the supplier, we first assume in a baseline scenario that cost and emission parameters are the same as those of the wholesaler with the only exception being inventory cost h_2 , which is adjusted by the supplier gross profit margin (assumed to be half of the wholesaler's gross profit margin, i.e., 6.74%) and estimated as 1.003 kilograms per year. We vary these values in subsequent scenarios. Parameters values for the baseline scenario are summarized in [Table 2](#).

In this example, the optimal number of trucks is 2 (see the proof of [Corollary 2](#) for the formula for the wholesaler's optimal number of trucks and order quantity). Using the data in [Table 2](#), one can verify that the conditions in [Corollary 2](#) (and [Theorem 1](#)) are satisfied for sufficiently large emission penalties. This implies that, in this example, total supply chain emission would indeed increase with increases in the emission penalty. For example, an emission penalty of \$0.4 per kilogram CO₂ would lead to a net increase of 0.62% in total supply chain emission. Note that we restrict our attention to penalty values up to \$0.4 per kilogram CO₂ to be consistent with prevailing carbon prices in practice ([World Bank, 2016](#)).

In addition to this baseline scenario, we carried out an extensive set of experiments where we varied the values of different parameters. For example, results shown in [Fig. 2](#) illustrate the impact of varying d_2 , the transportation distance for the wholesaler from its own supplier (while keeping all other parameters as in the baseline case). As we can see, in each of the scenarios shown, there are values of $t \leq \$ 0.4$ per kilogram CO₂, for which an increase in the emission penalty leads to an increase in total emissions, with the increase being more pronounced for large values of d_2 (e.g., when $d_2 = 3346$ kilometers, the distance between Chicago and Los Angeles, the increase in total supply chain emission can be up to 7.35% for $t \leq \$ 0.4$ per kilogram CO₂). Similarly, we also examine the effect of product price ([Table 3](#)). The average price of flour (calculated using average retail price discounted by the retail margin) is used to represent a low price (per kg) product, while the average price of potato chips is used to represent a high price (per kilogram) product. We can see that the emission increase is significant for the high price product.

⁵ Note that the estimation of $\hat{h}_1$ is independent on the function of the inventory, that is, it applies to all inventory types including cycle inventory and safety inventory.

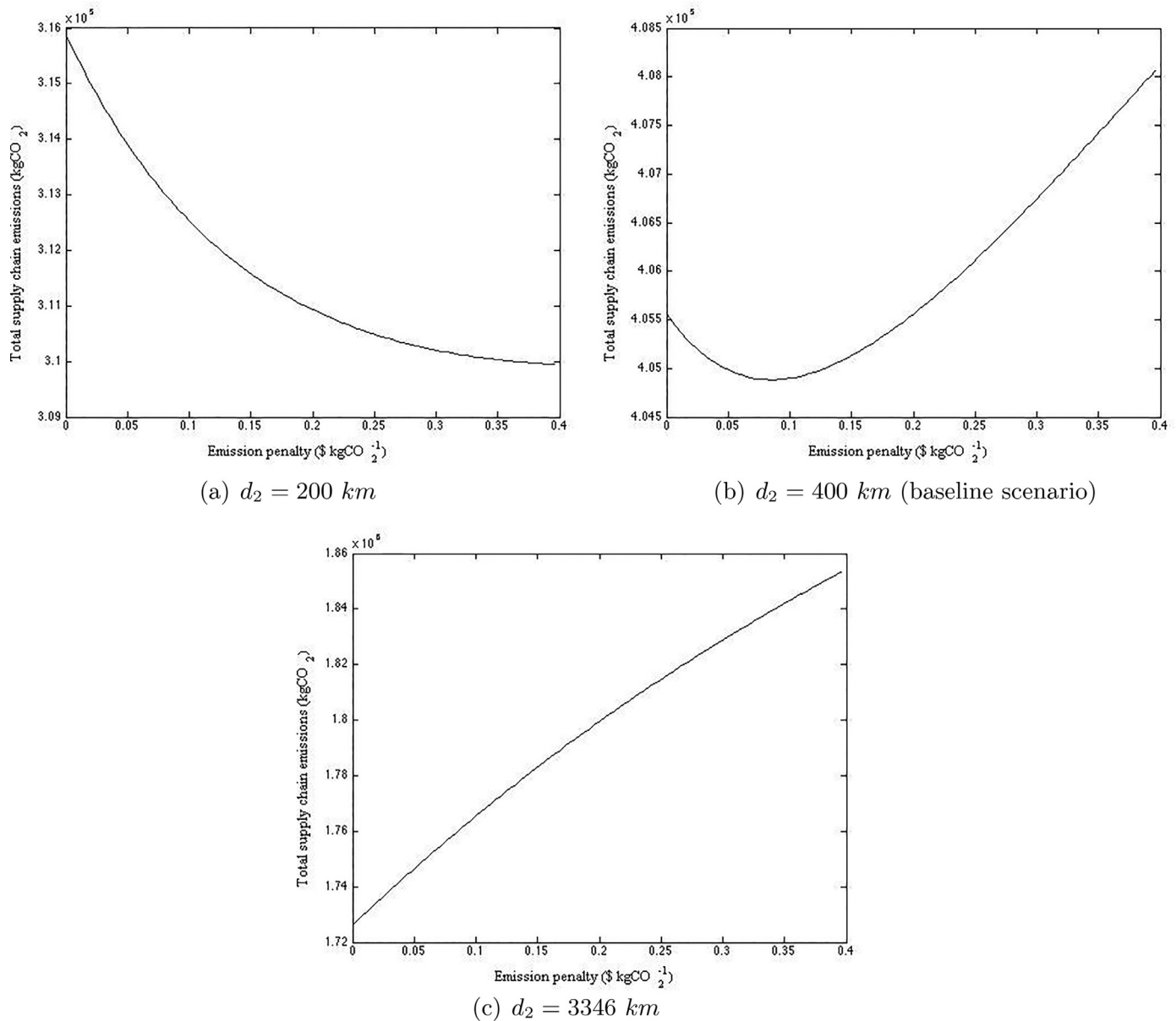


Fig. 2. The impact of the emission penalty on total supply chain emission.

Table 3

Product price baseline and alternative scenarios.

Scenario	p (\$ per kilogram)	Emissions always decrease with penalty?	Max emission increase (%)
Baseline (oranges)	1.93	N	0.62
Low cost (flour)	0.85	N	0.05
High cost (potato chips)	7.18	N	1.71

In Appendix E, we provide representative results where values of other parameters are varied. Out of the total of 19 scenarios considered, 16 exhibit net increases in total supply chain emission as the emission penalty increases. Although the increases are generally modest, they do suggest that introducing a penalty on emissions may not always be effective in reducing total supply chain emission for decentralized supply chains.

6. Concluding comments

The results in this paper highlight the potential risk of imposing emission penalties on firms in a supply chain without accounting

for the impact of the resulting emission mitigation efforts by individual firms on the other firms in the supply chain. We illustrated how such penalties could backfire and discussed scenarios under which this would occur. We show that this phenomenon occurs because firms's emission reduction efforts may create negative externality for other firms in the supply chain. We discussed potential remedies and highlighted the challenges associated with implementing these remedies. Finally, we provided a detailed analysis of a numerical example, where the lot-for-lot policy is used, to show that this phenomenon could occur under realistic values for cost and emission parameters. We observe that this phenomenon is more pronounced when the supplier's transportation distance

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